A Comprehensive Review of Modern Improvement Techniques of Direct Torque Control

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***Abstract*: One of the best control systems for controlling the torque of an induction machine is conventional direct torque control (DTC) (IM). The DTC's low switching frequency, on the other hand, creates large waves in flux and torque, resulting in acoustic noise that affects control performance, particularly at low speeds. Many direct torque control systems purported to solve these issues by concentrating just on torque and flux. This study presents a state-of-the-art overview of numerous recent strategies for increasing DTC control performance. The goal is to examine these approaches critically in terms of ripple reduction, tracking speed, switching loss, algorithm complexity, and parameter sensitivity. Furthermore, the material offered in this review study is expected to be a significant resource for academic and industrial researchers.**

***Keywords*: Induction Machine, Direct Torque Control, Fuzzy Logic Control.**

I. INTRODUCTION

Electric motors utilise more than half of the electrical energy produced in industry. Three-phase induction machines (IMs) are one of the most common forms of electric motors. Indeed, induction motors are used in at least 80% of industrial control systems, and they have increasingly replaced DC machines due to their superior performance: dependability, simplicity of design, cheap cost, and ease of maintenance [1, 2]. However, these various benefits are not without drawbacks; the machine's dynamic behaviour is frequently quite complicated [3, 4], since its modelling results in a system of nonlinear equations that are tightly linked and multivariable.

Furthermore, certain of its state variables, such as flux, are not measurably observable. To manage the torque and flux of these devices in real time, more complex control algorithms are required. Academic and industrial research has been conducted for numerous years to address the IM's control challenge and provide strong and efficient controls [5].

In this context, scalar control is the initial approach for controlling electrical devices; this control strategy entails maintaining the V/f constant to maintain the flux in the machine [6, 7]. It is distinguished by its ease of implementation and its straightforward structure, which is based on stator flux control. The flux oscillates vigorously with significant amplitudes at start-up or to alter the machine's rotation direction, and its modulus is varied during transient states. These oscillations will affect the quality of the torque and speed, decreasing the machine's performance in the transient condition. As a result, this sort of control is limited to applications with low speed variations, such as pumping or ventilation [8, 9].

To regulate transient torque, the Field Oriented Control (FOC) approach was developed later. This control allows the IM to behave similarly to a DC machine with a decoupling between torque and flux. This decoupling allows for a very quick torque response, a wide speed control range, and excellent efficiency across a wide load range. However, this control is very sensitive to machine parametric fluctuations, particularly those of the resistors, whose value varies significantly with temperature [10-12]. Any discrepancy between the parameters utilised by the FOC algorithm and the machine's real parameters is translated into mistakes in the flux and torque output values, resulting in greater machine losses and lower control system performance [12].

Direct Torque Control (DTC) was introduced in the middle of the 1980s to compete with traditional controls. TAKAHASHI [13] and DEPENBROCK [14] were the first to use this approach. It boasts exceptional dynamic performance as well as strong resilience in the face of machine parameter fluctuations. It works on the basis of a direct determination of the control pulses given to the voltage inverter switches. However, there are two important drawbacks:

(i) the switching frequency is very variable, and
(ii) the torque and stator flux undulations are poorly regulated across the speed range of the intended operation.

It should be noted that torque ripples produce extra noise and vibrations, resulting in rotating shaft disturbances. A lot of research is now being done to try to tackle these issues. Artificial Intelligence (AI) control is a term that has gained popularity in recent years and now has a significant presence in current research disciplines. The three primary AI families are fuzzy logic, neural networks, and genetic algorithms. The authors of [15-19] present AI strategies to improve the dynamic performance of DTC control. These control methods may provide performance optimization under various operating situations, such as torque and flux ripple reduction, THD reduction, efficiency improvement, energy savings, and so on.

Different studies exploring DTC methods for induction motor drives have been published, but these schemes have not been properly analysed. The goal of this study is to provide researchers who are interested in the present state of the art of DTC strategy and work on new lines of research an idea of how to examine several modern strategies for enhancing the performance of direct torque control.

II. DIRECT TORQUE CONTROL

Takahashi [13] and Depenbrock [14] suggested direct torque control (DTC) for induction machines in the middle of the 1980s. It is less susceptible to machine parametric fluctuations than vector control, and its control technique is simple due to the lack of pulse width modulation (PWM), Current Controllers, and Park Transformations [20, 21]. It does not employ PI regulation loops, which should increase its dynamic capabilities and remove difficulties associated with PI regulator saturation. DTC management enables great efficiency as well as precise and quick torque dynamics. The DTC idea is based on applying a control sequence directly to the voltage inverter switches (switching states) located upstream of the machine [22]. A switching table and two hysteresis regulators are used to choose this sequence. Their purpose is to manage and regulate the machine's electromagnetic torque and flux in a decoupled way. The DTC control is depicted in Figure 1 as a basic structure. A three-level hysteresis comparator is used to control the electromagnetic torque. A two-level hysteresis comparator is used to regulate the stator flow. The switching table is determined using the outputs of these comparators as well as the flux vector information.

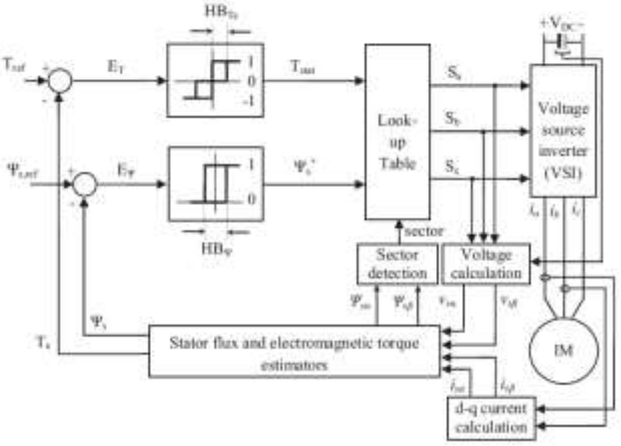

Fig 1: Direct Torque Control of Induction Motor

To achieve optimal performance in DTC, the precision of electromagnetic torque and stator flux measurement is critical [23]. So, the stator current is monitored, while the stator voltage is determined by the switching state (Sa, Sb, and Sc) created by the switching table and the DC link voltage Udc [24]. The Concordia transformation transforms these parameters into coordinates (α, β), which are suitable for the DTC method.

The stator flux ψs and the electromagnetic torque Tem are estimated from the following equations:

$$\Psi s = \sqrt{\psi s\alpha^2 + \psi s\beta^2}$$

$$\text{Tem} = \text{p.}(\ \psi s\alpha.is\beta - \psi s\beta.is\alpha)$$

$$\Psi s\alpha = \int_0^t (Vs\alpha - Rs.is\alpha).dt$$

$$\Psi s\beta = \int_0^t (Vs\beta - Rs.is\beta).dt$$

The estimated values of the electromagnetic torque Test and the stator flux est are then compared to their respective reference values Tem* and s*, with the comparison results serving as inputs to the hysteresis comparators [25]. The control table is used to pick the suitable voltage vector (Table 1). The flux sector number and the outputs of the two hysteresis comparators are the table's inputs.

Despite its ease of use, durability, and speed, the DTC control has significant drawbacks. High ripples in the flux and electromagnetic torque induce mechanical vibrations and unwanted acoustic noise, resulting in a worsening of machine performance, as well as a variable switching frequency and current distortions, which can affect the quality of the output power. At low speeds, stator resistance is neglected, resulting in issues. Furthermore, the actual implementation of hysteresis-type nonlinear components necessitates a short sample time and, as a result, a high computation frequency, resulting in limiting designs [26].

Many direct control solutions have arisen in recent years to address the issues with traditional DTC. The principles of instantaneous torque and stator flux regulation, as well as the direct calculation of inverter control signals from a switching table, are shared by both systems. In general, there are two types of control methods: traditional and new procedures. Vector Spatial Modulation (SVM), sliding mode based DTC, model predictive DTC, and artificial intelligence (fuzzy logic, neural network, and genetic algorithm) [27-29] are only a few examples. The approaches utilized to enhance the DTC control of an induction machine are classified in Fig. 2.

Table 1: Optimal Switching Table

Flux	**Torque**	**Voltage Sector**					
		1	**2**	**3**	**4**	**5**	**6**
1	1	V2	V3	V4	V5	V6	V1
	0	V7	V0	V7	V0	V7	V0
	-1	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

III. THE MAJOR PROBLEM IN BASIC DTC SCHEME

Despite its simplicity, the basic DTC method based on hysteresis controllers has a number of significant shortcomings, including variable inverter switching frequency, large torque ripple, and hence a high sampling need to reduce digital implementation difficulties [14,20,21,23–28].

3.1 Variable Inverter Frequency

The switching frequency of the voltage source inverter (VSI) is entirely determined by the switching in the hysteresis comparators in the basic DTC [23]. Operating conditions (i.e. rotor speed, stator and rotor fluxes, and DC link voltage) change the slopes of torque and flux, which impact switching in their hysteresis comparators [22]. As a result, the switching frequency of VSI varies depending on the operating circumstances. As a result, most operational situations cannot fully exploit the switching devices' maximum frequency capabilities, because the hysteresis bandwidth is chosen based on the worst-case scenarios [30].

3.2 High Torque Ripple

The output torque is computed in digital implementation, and the necessary switching states are determined at a given sampling period (which is DT in Fig. 1). This, however, creates a delay between the time the variables are sampled (i.e. the time the torque is computed) and the time the inverter receives the matching switching state. As a result, the torque ripple cannot be precisely contained inside the hysteresis band. However, if the band is set too small, the torque ripple is not reduced. This is because there is a chance that the calculated torque may exceed the torque hysteresis range, causing the reverse voltage vector to be selected. As previously stated, choosing the reverse voltage vector causes the torque to rapidly drop, increasing the torque ripple [31].

3.3 The need for high speed processor

When the processor employed has a restricted sampling frequency, reducing torque ripple by lowering the bandwidth of the hysteresis comparator is pointless. All of the foregoing limits can be removed if a high-speed CPU is used, with a discrete hysteresis controller that functions similarly to an analogue based comparator. If the sample time(DT) is suitably reduced, the quick drop in torque owing to reverse voltage selection may be prevented [32].

Some experimental findings of output torque ripple generated in hysteresis-based DTC at different applied sampling frequencies and/or torque hysteresis bands are shown in Fig. 2(a)–(c) in earlier investigations [31, 32]. The torque control at 6Nm was done in each example at the same load torque situation, resulting in a rotor speed of roughly 400rpm. The nominal torque hysteresis band level is HBTe (0.9 Nm), and the digital signal processing (DSP) minimum sampling time is 55 s.

When the torque hysteresis band is adjusted to double HBTe, the output torque ripple is significant, as seen in Fig. 2(a). As a result, the hysteresis band may be reduced to lessen the torque ripple of the conventional DTC method. When the torque hysteresis band is reduced to HBTe, the output torque control results are shown in Fig. 2(b). However, because the sampling time in Fig. 2(a) and(b) is twice the nominal DT (i.e.110 s), this results in inaccurate or reverse voltage vector choices (where Tstat1 1), which produces fast drops in output torque and hence increases torque ripple, as shown in Fig. 2(a) and(b) (b). As a result, the sample time must be lowered to eliminate reverse voltage vector choices, as shown in Fig. 2(c), where the sampling is set at DT. The output torque ripple reduces, as seen in Fig. 2(c), and no active voltage vector is selected to lower the torque.

Essentially, the output torque ripple may be decreased by lowering the hysteresis comparator's bandwidth to a reasonable amount. The suitable bandwidth is chosen based on the worst possible operational circumstances. This ensures that switching device switching frequency does not exceed its limit (or thermal restriction). It's also a good idea to utilise a fast processor to maintain the ripple inside the band, so that the discrete hysteresis controller behaves like an analogue one. The usage of Field Programmable Gate Arrays (FPGA) is the best option to run the DTC algorithm at the greatest sampling rate with a cheap cost and fast processor [33].

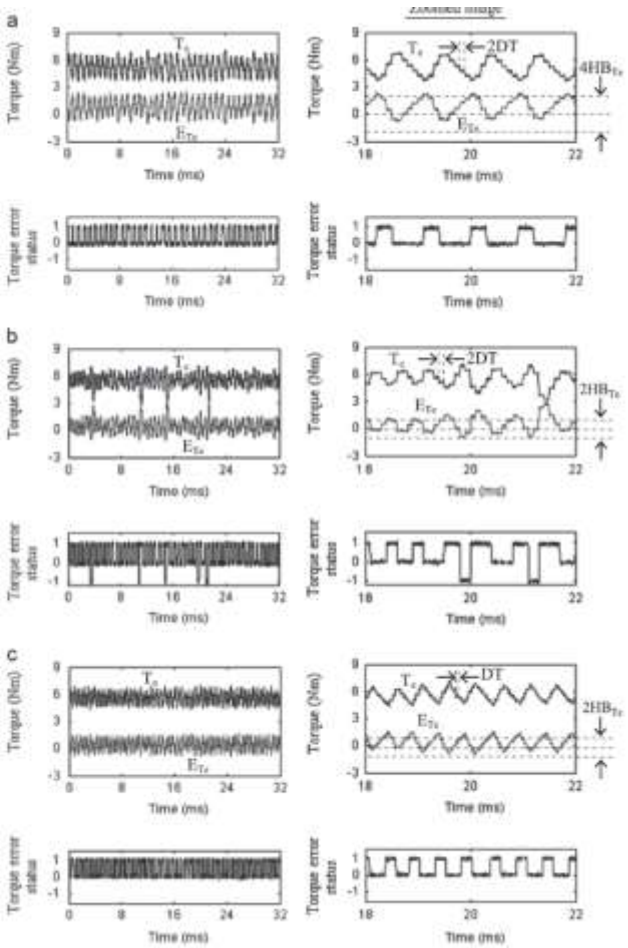

Fig 2: Control of output torque utilizing three level hysteresis comparator

IV. IMPROVEMENT TECHNIQUES OF DIRECT TORQUE CONTROL

Several publications [34, 35] have employed the Space Vector Modulation (SVM) approach to enhance DTC by adjusting the voltage inverter. The concept of this technology is to impose the necessary tension vector by vector modulation of space in order to proceed to predictive torque and flux management. Although the control algorithm for this technique is more complicated, flux and torque oscillations are decreased, and the inverter's average switching frequency becomes constant [36]. During a realistic implementation, the DTC-SVM, like any predictive approach, has some static torque error for control without a speed loop. This inaccuracy is caused by the calculation time required for the control voltage prediction.

The authors of [34] devised a mechanism for obtaining a constant switching frequency. The Takahashi selection table and the hysteresis comparators are both eliminated in this technique. The PWM approach is utilized to create the control's output vector in this case. The goal of this method is to get direct control of the stator flow vector in a stator-linked frame (α, β). The intended switching periods may be calculated using the projection components of the desired stator voltage vector on the two neighboring voltage vectors of the frame (α, β).

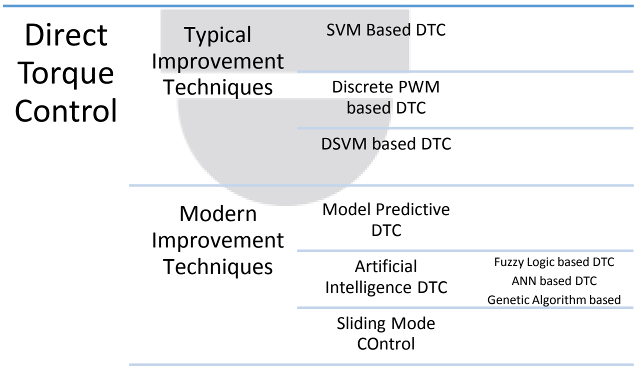

Fig 3: DTC Improvement Techniques Classification

A method of direct torque control of the IM based on pulse width modulation (PWM) with a constant switching frequency was proposed in [35, 36]. To allow implementation on microcontrollers or DSP boards, the proposed control technique is developed in discrete time. The authors use simulations and experimental tests to validate the proposed method. In [37, 38], the authors showed that the conventional DTC has a low number of voltage vectors applied to the machine, which causes undesirable oscillations of the torque, flux and current.

This research demonstrates that a novel DTC method based on the use of SVM for defined time periods can increase performance. Using a five-level torque comparator, a Discrete Space Vector Modulation (DSVM) produces a greater voltage vector number. With a set switching frequency, numerical calculations and actual experiments reveal enhanced torque and flux responsiveness.

The DTC has been developed for the control of machines powered by inverters of multilayer voltage types [39], and the bigger the number of control vectors, the lower the resultant ripple in steady state. For the minimization of torque ripples, a three-level inverter is applied to the DTC in [39], but the downside of this arrangement is the expensive cost. They're particularly handy in high-power controllers.

V. MODERN IMPROVEMENT TECHNIQUES OF DIRECT TORQUE CONTROL

5.1 Sliding Mode Control based DTC

Sliding Mode Control (SMC) is a kind of Variable Structure Control (VSC) proposed by Utkin [40]. It is well recognised for its resilience against internal uncertainties (machine parameter fluctuations), external uncertainties (load disturbance), and phenomena that were not modelled. The major characteristic of SMC is exhibited in a discontinuous way in the modified control law. However, there are certain disadvantages: the development of the chattering phenomena produced by the discontinuous portion of the control, which may be harmful to the machines [41], the system is subject to high control at all times in order to assure its convergence to the goal, which is undesirable.

DTC for IMs was improved using the SMC approach [42, 43]. These methods increase steady-state performance while preserving the benefits of the transient state. The authors begin to employ a discrete time sliding mode control method in [44] to ensure that the torque and flux are resistant to changes in machine parameters. The reference voltages (Vsa,Vsb) are supplied by the controllers for application to the IM, and no controller current is utilised. The reference voltage vector is computed via a PWM vector system and a fixed switching frequency is employed, unlike other sliding mode systems. The efficiency of the suggested technique is demonstrated through simulations and experimental data. The overall scheme of the direct torque control structure and flux based on the sliding mode of an induction machine (DTC-SMC) regulated in speed is depicted in Fig. 3. It's a command that controls the electromagnetic torque, the square norm of the flux, and the speed in a cascade fashion. In order to change the torque, flux, and speed, sliding regimes control algorithms must be included in the control structure. The flux and torque estimator in the "estimator" block only uses the voltage and stator current measurements in the reference (,). This control system is both quick and reliable. The regulated magnitude, on the other hand, causes unwanted chattering.

Other studies employed the robust sliding mode observer [45] to reduce the sensitivity of flux estimates to measurement noise.

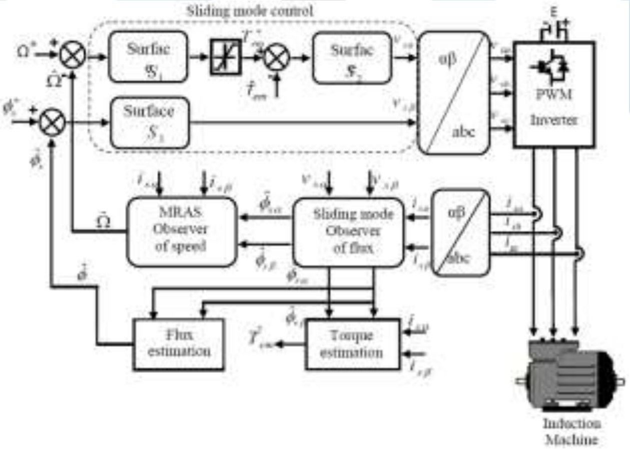

Fig 4: Sliding Mode Control based DTC of Induction Motor

5.2 Model Predictive Control based DTC

Predictive control is an advanced automated control approach. Its goal is to regulate complicated industrial systems. The premise behind this method is to compute the system's future behaviour based on the dynamic model of the process inside the real-time controller, and then utilise that knowledge to generate the best values for the adjustment parameters [46]. Model predictive control (MPC) has shown to be effective in the realm of digital controls in terms of speed and accuracy [47].

The predictive control technique for DTC has recently attracted a lot of interest, owing to its potential to reduce torque and flux ripples while minimising the switching frequency of the voltage inverter that powers the machine. In DTC-MPC, an online optimization algorithm replaces the typical DTC switching table [48-50]. In predictive control, the theory of vector selection is based on the assessment of a given cost function. The controllable variables' future behavior is predicted using a predictive model that includes stator flux, torque, and angular velocity. Figure 4 shows a simplified schematic of the DTC-MPC.

The predictive algorithm's execution may be broken down into three steps:

- Estimation of variables that aren't quantifiable.

- The forecasting of the system's future behaviour.
- The optimization of the control outputs using a previously determined cost function.

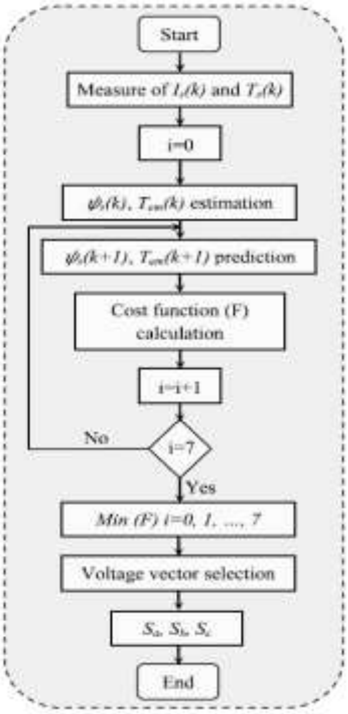

Fig 5: Algorithm for Model Predictive Control based DTC

At each sampling time step, these procedures are repeated, taking into account the new measurements. Feedback from measurements is utilised to forecast and decide on methods to minimise the value of the cost function F, resulting in closed-loop control. The DTC-MPC flowchart is shown in Figure 5. The MPC idea is relatively basic and straightforward, easy to implement, the limitations and nonlinearities of the systems to be managed may be incorporated in the control, and the case of multi-variable systems can be taken into account. Predictive control offers several advantages. However, in comparison to traditional DTC, this sort of control necessitates a lot more online calculation. A predictive control technique based on the optimization of a cost function defined on a horizon was described in [51, 52] to ensure disturbance rejection, enhance resilience to parameter fluctuations, and make the system more efficient. In addition, the authors suggest a strategy to improve the dynamic performance of the DTC utilising predictive control in [48-50], demonstrating that DTC-MPC delivers improved performance in terms of dynamics evaluated quickly, torque and flux ripple reduction, and current shape improvement.

5.3 Fuzzy Logic Based DTC

Fuzzy logic, or the management of uncertainty in general, is a type of artificial intelligence [53] that was developed to enhance the performance of many traditional control systems for variable speed drives. The Fuzzy Direct Torque Control (FDTC) approach is proposed by the authors in [54, 55] to improve the dynamic performance of traditional DTC control. They create a new selection table based on a fuzzy logic controller (FLC) to replace the switching table and hysteresis comparators and generate the vector voltage that optimally drives the flux and torque to their references. The FDTC instruction issued to the induction machine has a general structure, as shown in Fig. 6.

The stator flux error, electromagnetic torque error, and stator flux vector position are inputs to the fuzzy switching table, while the switching states of the inverter arms (Sa, Sb, Sc) are outputs [56–58]. To achieve greater control with the fewest rules possible, each input and output is separated into a predetermined number of fuzzy sets. The inference rules are built in a fashion that allows for the correction of disparities between the flux and torque set-points and their estimated values. The domain of the stator flux vector's angle is represented by six linguistic variables. Tem's speech universe is fuzzified using three linguistic variables (N: negative, Z: zero, and P: positive). Furthermore, the speech universe of is fuzzified using two linguistic variables (N: negative and P: positive). Each output's discourse universe is partitioned into two fuzzy sets (zero and one). Figure 7 depicts the membership functions and inference rules used to create the fuzzy table.

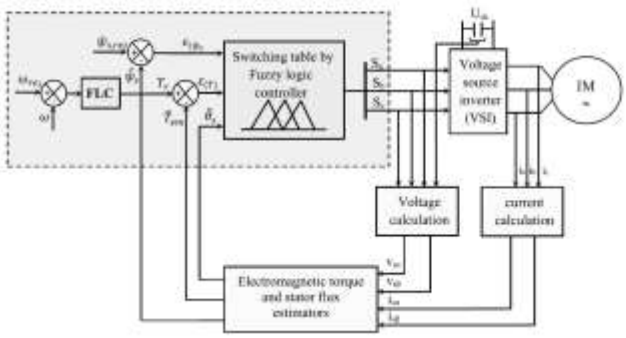

Fig 6: **Fuzzy Logic Control based DTC of Induction Motor**

The authors developed a fuzzy logic-based DTC approach in [59]. The goal of this project is to increase the DTC control's performance while reducing torque at low speeds. They've included a fuzzy speed regulator that allows them to modify the integration coefficient ki and the coefficient of proportionality kp dynamically as a function of the error and speed fluctuations. In addition, a fuzzy controller is used to replace the flux and torque hysteresis in order to maximise the voltage vector selection. The experimental findings demonstrate that the suggested fuzzy control system can offer a quick reaction and high accuracy in steady state speed, as well as a significant decrease in torque ripples even at low speeds. Furthermore, fuzzy logic is employed to manage the boundaries of the electromagnetic torque hysteresis band, resulting in torque undulation reduction and improved dynamic performance. Uddin Nasir et al. [60] presented a fuzzy controller to change the hysteresis band in real time in the same scenario. The fuzzy controller finds the optimum bandwidth of the torque hysteresis based on the slopes of the fluctuation of the predicted torque and the stator current. The performance of this fuzzy controller is demonstrated by simulation results using a model generated in Matlab/Simulink, as well as experimental data produced with a DSP board. The torque ripple of the suggested control was significantly decreased in comparison to the traditional DTC, according to a comparison study between the DTC based on the proposed fuzzy controller and the conventional DTC.

The use of control tables produced by fuzzy logic reasoning is employed in [61] to investigate the influence of parametric variation on DTC performance. The simulation results have confirmed the validity of the suggested strategy. Fuzzy logic can deal with unknown parameters. However, the primary drawbacks of this method are the difficulty in fine-tuning fuzzy logic parameters and the complexity of implementation; this is due to the fact that fuzzy controllers employ a large number of rules to conduct comprehensive tests.

5.4 Artificial Neural Network Based DTC

In various domains of technology and scientific inquiry, the Artificial Neural Network (ANN) is frequently employed. This strategy can be used to solve tough issues that are difficult to control and cannot be explained by exact mathematical approaches. These neural networks have a wide range of applications, including classification, image and audio processing, estimation, process identification [62, 63], and electrical system management [64, 65]. The authors of [65] integrated artificial neural networks into the control of an induction machine, stating that the efficiency of the PI regulator deteriorates and the quality of the adjustment deteriorates in some cases where the dynamics of the system change over time and/or with operating conditions. The authors have integrated artificial neural networks into the speed control to address these issues and ensure that the command performs well. To evaluate the contribution of ANN, many tests were simulated. The acquired findings allow for the affirmation of improved performance and robustness in the IM's control.

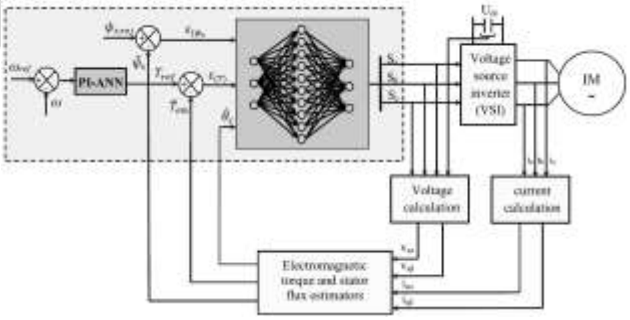

Fig 7: **ANN based DTC of Induction Motor**

The use of the ANN approach to choose the states of the voltage inverter switches used to power the DTC-controlled IM has been recommended in several publications [62-65]. The goal is to replace the traditional switching table that determines inverter states with a neural selector that can manage control signals in a similar manner. The block diagram of Direct Torque Neural Control is shown in Figure 8. (DTNC). A multilayer neural network is used in the design to replace both hysteresis comparators and the selection table. An input layer, two hidden layers, and an output layer make up this neural network. The torque error, the flux error, and the angular location () of the stator flux vector are the three neurons that make up the input layer. Each of the two buried layers has 10 neurons. Three neurons make up the output layer, which generates the reference voltage that is delivered across the IM through the voltage inverter. In comparison to other standard approaches, the use of neural networks in DTC enables a strong dynamic response of torque and flux with a fixed switching frequency, resulting in a significant reduction in torque ripples and the harmonic rate of currents [66]. Furthermore, it is extremely resistant to different motor parameter uncertainties [67]. However, this proposed approach has the drawback of a more sophisticated internal structure.

5.5 Genetic Algorithm based DTC

Genetic Algorithms (GAs) are a diverse and fascinating set of stochastic optimization algorithms that are based on natural evolution and genetics approaches [68]. These algorithms work on the basis of a stochastic search across a huge space and a population of pseudo-solutions [69]. One of the key benefits of genetic algorithms is their robustness against parametric fluctuations; they allow for the provision of one or many high-quality solutions to a wide range of problems with a relatively minimal investment (time and computer resources) [70]. However, it has the drawback of parameter selection, since the choice of these parameters is highly dependent on the investigated topic and the user's knowledge of the problem. The evolutionary algorithm has recently been applied to improve the dynamic performance of the DTC control; it is well fitted to optimize the speed controller gain values [71, 72].

The optimization technique (GA) has been applied to DTC in [71], with the authors using a PI regulator optimized by the genetic algorithm (PI-GA). This method outperformed conventional DTC in both transient and stable states, with many benefits confirmed, including torque and flux ripple reduction, overshoot reduction, and response time reduction.

The authors of [73] developed a novel DTC technique that optimizes the PI-fuzzy regulator using a genetic algorithm. In this technique, an adaptive regulator PI-fuzzy of speed adjusts the integral coefficient ki and proportional kp in real time as a function of the speed error and its derivative with respect to time. The genetic algorithm refines the fuzzy parameters to increase the speed's self-adaptation. In addition, to enhance the choice of the voltage vector, the hysteresis regulators have been replaced by another fuzzy regulator. Finally, the author conducted a comparison of Takahashi's traditional DTC, PI-fuzzy regulator, and the suggested method. This research demonstrated a considerable reduction in ripples at the torque, flux, and current levels. As well as increasing tracking accuracy and speed.

5.6 Comparative Analysis

The recommended approaches for increasing the performance of direct torque control in an induction machine are critically analysed in Table 2. The purpose of this analysis is to highlight a concept for scholars interested in the DTC approach. The torque and flux ripple, switching frequency, parameter sensitivity, steady-state and dynamic responsiveness, and algorithm complexity are all factors in the evaluation of these approaches. It is important to note that assessment does not have a completely absolute meaning because it is impossible to locate numerous works created under the same conditions and on the same sort of machine; yet, the essential drawbacks and advantages for each control approach must be the same.

According to this research, traditional DTC has the simplest structure among the other control techniques with a low switching frequency, which is DTC's main flaw. The sampling frequency must be high in order to overcome these issues and get a suitably low torque ripple. Under the same sampling frequency, artificial intelligence approaches and the predictive model of DTC may achieve lower torque ripple and switching frequency than direct torque control, but the complexity of AI methods is significantly higher. As a result, it may be used in high-power applications for high-precision control. Furthermore, while SVM and SMC algorithms can help enhance DTC, they have drawbacks such as sensitivity and chattering. The best way to overcome the complexity problem is to simplify the control algorithm without expanding the microprocessor's calculating capabilities. On the other hand, establishing a hybrid control method that combines two or more current techniques can increase the performance of the DTC drive while also resulting in a low-cost system.

Table 2: Comparative Analysis of All Direct Torque Control Techniques

	Conventional DTC	*SVM based DTC*	*SMC based DTC*	*Model Predictive Control based DTC*	*Fuzzy Logic based DTC*	*ANN based DTC*	*GA based DTC*
Torque Response	Fast	Fast	Fast	Fast	Very Fast	Very Fast	Very Fast
Torque and Flux ripple	High	Low	Medium	Low	Very Low	Very Low	Medium
Current Distortion	More	Less	Less	Less	Less	Less	Less
Switching Frequency	Variable	Constant	Nearly Constant	Constant	Constant	Constant	Nearly Constant
Dynamic at Low Speed	Poor	Good	Good	Good	Very Good	Very Good	Very Good
Algorithm Complexity	Simple	Simple	Complex	Simple	More Complex	More Complex	Complex
Computation Time	Low	Medium	High	Medium	High	High	Medium

VI. CONCLUSION

Several recent direct torque control strategies for an induction motor are reviewed in this work. The goal of this enhancement is to reduce the switching frequency of the inverter while minimizing the ripples of the flux of the IM. These solutions are classified and compared in terms of ripple reduction, tracking speed, switching loss, algorithm complexity, and parameter sensitivity. It's tough to say which approach is the best for improving DTC performance. The approach used is determined by the application, cost, hardware availability, system dependability, and accuracy. This evaluation is considered to be a valuable resource for all sectors and researchers interested in electrical machine controls.

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